LBNL Superconducting Magnet Program
Accelerator and Fusion Research Division
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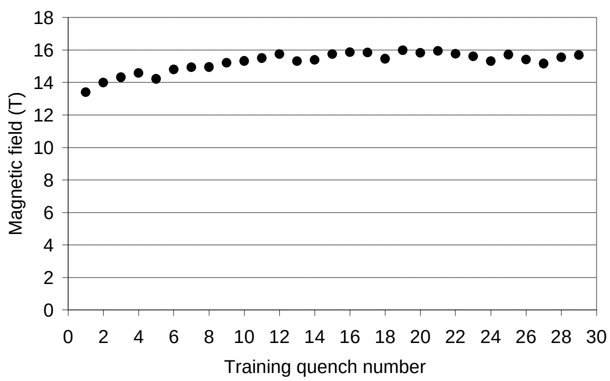
HD-1 Sets New Dipole Field Record

On October 9, 2003, the Nb_3Sn dipole HD-1 achieved its design field of 16 Tesla, surpassing by more than one Tesla the previous field record, set by the RD3b dipole in April 2001. The test started on October 8, 2003, with a first quench at 13.4 Tesla and rapid progress to 14.8 Tesla (above RD3b level) in five more quenches. About 30 training ramps were performed during the first cool-down cycle. After nine quenches, the magnet consistently reached fields above 15.2 T, with five quenches above 15.8 T.



HD-1 training history (first thermal cycle)

HD-1 Goals

Testing Nb_3Sn stress limits above 150 MPa

High field dipoles and quadrupoles are required for upgrades of particle accelerators such as the LHC, as well as for future hadron colliders at the energy frontier. At present time, Nb_3Sn is the only practical superconductor available for design fields above 10 Tesla. However, Nb_3Sn is brittle and strain sensitive, requiring special design and fabrication methods to be used effectively. The LBNL program has been developing Nb_3Sn accelerator magnet technology for the past 20 years. In a series of magnet tests, we have achieved progressively higher fields using Nb_3Sn in a variety of coil configurations. During the 1980s, the development of “wind-and-react” technology resulted in fabrication and test of the block-coil dipole D10, up to 8 T. In the 1990s, the cosθ dipole D20 reached a field above 13 T. In 2001, the dual-bore common coil dipole RD3b surpassed 14 T.

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Senior Program Officer, Dr. David Sutter

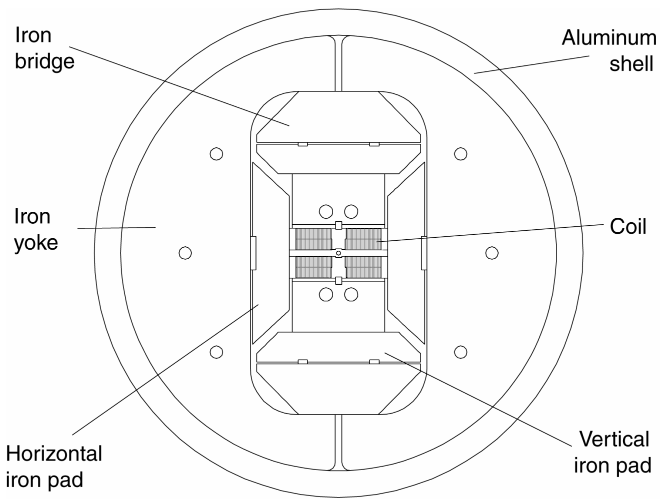
HD-1 is a block-coil dipole designed to push the limits of accelerator magnet technology to unprecedented levels in terms of magnetic field and mechanical stresses. The magnet uses state of the art conductor with a critical current density of 3 kA/mm^2 at 12 T, 4.2 K. This conductor, developed by Oxford Instruments Superconducting Technology, is suitable for generation of very high fields in practical accelerator designs. However, the associated mechanical stresses may cause severe degradation of the conductor properties. Until recent years, this effect was believed to represent a major performance limitation for Nb_3Sn accelerator magnets.

After the D-20 and RD3b dipoles demonstrated successful operation up to a coil stress of 120 MPa, we designed HD-1 to investigate the conductor performance under stress levels above 150 MPa. A single-bore block-coil geometry was selected, marking a return to configurations developed during the early stages of the LBNL Nb_3Sn program. This choice is motivated by the following factors: physical separation between high-field and high-stress points; use of flat cables with minimal degradation; simple winding procedures, end parts, support structures, assembly techniques; modularity of the coil package; potential for high conductor packing and efficient coil grading; compatibility with force bypasses to avoid stress accumulation. Most of these advantages are shared with the common coil configuration (RD series). However, single-aperture block-coils allow for more efficient R&D (smaller conductor volume, magnet size, stored energy) and are compatible with the horizontal layout in dual-bore dipoles, which has magnetic and mechanical advantages with respect to a vertical layout.

HD1 assembly. The outer diameter of the shell is 74 cm.

HD-1 Design and Fabrication

HD1 presented many new design challenges with respect to the common coil dipoles we have developed in recent years. Of particular concern were (a) the high coil stresses, of the order of 150 MPa; (b) the high field and forces in the end regions; (c) the interlayer ramp, located in a high field region next to the pole; (d) the orientation of the main Lorentz forces, corresponding to the direction in which the coil package is more compliant and therefore more subject to displacements and the associated stick-slip motions. To respond to these challenges, a full 3D prestress system was implemented, and design features were introduced to reduce the end field.



HD1 magnet cross-section. The outer diameter of the shell is 74 cm.

The magnet combines two double-layer racetrack modules in a block-coil configuration. The turns are wound around an iron island, with a minimum bending radius of 10 mm. A 10 mm thick G10 plate separates the coils and provides a clear aperture of 8 mm in diameter. The use of an iron pole enhances the bore field by about 0.6 Tesla with respect to the conductor peak field in HD-1. However, we plan to eliminate the iron pole in future HD models to reduce saturation effects. A roughly equivalent field contribution will be recovered by implementing a flared end design with no midplane gap.

The support structure is composed of horizontal and vertical iron pads, iron bridges, iron yoke and aluminum shell. The yoke and the shell were previously used for the RD series of dual-bore common coil magnets. During the magnet assembly, pressurized bladders compress the coil-pack both in the vertical and in the horizontal direction. At the same time, the yoke halves are pushed apart and the aluminum shell is pre-tensioned. Eight interference keys lock the pre-stress and allow for bladder removal. Four aluminum rods, pre-tensioned during assembly, assure adequate axial pre-stress in order to minimize conductor displacements in the coil end regions. The thermal contraction differentials between yoke and shell are exploited to generate a large increase of the pre-stress during cooldown, preventing over-stress and possible conductor damage at room temperature.

HD-1 Test Results

The successful performance of brittle Nb_3Sn coils in a realistic dipole configuration under a stress of 150 MPa is the most important outcome of the HD-1 test. The block-coil geometry requires full pre-stress to prevent conductor separation from the pole at high field, and the associated stick-slip motions under large axial forces. Lorentz stress accumulation during magnet excitation is not a major concern in a block-coil design, since it occurs in a region where the field is low and margin is available. However, high pre-stress can cause damage and permanent degradation of the conductor in the high-field pole region, limiting the magnet performance. In this respect, the bladder and key technology is essential to avoid over-stressing the coils during magnet assembly, but poses design challenges due to the large stress build-up during cooldown, when no adjustments are possible. For this reason, during the initial HD-1 assembly we elected to limit the pre-stress to 150 MPa, corresponding to a design field of 16.2 T. This pre-stress level was not sufficient to reach the conductor limited quench field, calculated under the most optimistic assumptions (no conductor degradation with respect to the performance of virgin strands). However, it was sufficient to reach a record-high field and to confirm the magnetic, mechanical and quench protection design calculations.

Up to this point, there is no evidence of degraded performance due to cabling, high pre-stress and Lorentz-stress, as well as the use of hard spacers and high-field inter-layer transitions. The HD-1 training stopped at a field and force level corresponding to the design pre-stress. An increase of the pre-stress will be attempted as a next step, to realize the full theoretical performance of the conductor. We are also considering a test at 1.9 K as a means to achieve fields above 17 Tesla.

Subsequent dipoles in the HD series will introduce a larger clear bore and better field quality. At the same time, a further increase of the dipole field will be pursued using a combination of improved conductor, flared ends with no midplane gap, and graded coils, with both Nb_3Sn and HTS inserts.

Selected Publications

S.E. Bartlett, P. Bish, S. Caspi, L. Chiesa, D.R. Dietderich, P. Ferracin, M. Goli, S.A. Gourlay, R.R. Hafalia, C.R. Hannaford, H. Higley, W. Lau, A.F. Lietzke, N. Liggins, S. Mattafirri, A.D. McInturff, M. Nyman, G.L. Sabbi, R.M. Scanlan, J. Swanson, "*HD1: Design and Fabrication of a 16 Tesla Nb_3Sn Dipole Magnet*", Proceedings of the MT-18 Conference, Morioka, October 2003.

S.E. Bartlett, P. Bish, S. Caspi, L. Chiesa, D.R. Dietderich, P. Ferracin, M. Goli, S.A. Gourlay, R.R. Hafalia, C.R. Hannaford, H. Higley, W. Lau, A.F. Lietzke, N. Liggins, S. Mattafirri, A.D. McInturff, M. Nyman, G.L. Sabbi, R.M. Scanlan, J. Swanson, "*Test Results for HD1, a 16T Nb_3Sn Dipole Magnet*", Proceedings of the MT-18 Conference, Morioka, October 2003.

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